HYBRID ELECTRIC VEHICLES

UNIT-1

1.Introduction Fundamentals of vehicle components of conventional vehicle and propulsion load:

2.1 LONGITUDINAL VEHICLE MODEL

In practical terms, a vehicle not only travels on a level road but also up and down the slope of a roadway as well as around corners. In order to model this motion, the description of the roadway can be simplified by considering a straight roadway with two-dimensional movement. This two-dimensional model will focus on vehicle performance, including acceleration, speed, and gradeability, as well as braking performance.

Figure 2.1 shows the forces acting on a vehicle as it travels at a given speed along a roadway with a specific grade. Fundamental principles of mechanical systems can be used to express the relationship between the vehicle acceleration and the forces acting on the vehicle body as:

$$ma = F_t - F_w - F_g - F_r \tag{2.1}$$

where m is the vehicle mass, a is the acceleration of the vehicle. F_t is the total tractive force acting upon the vehicle body, F_w is the aerodynamic drag force, F_g is the grading resistance force, and F_r is the rolling resistance force.

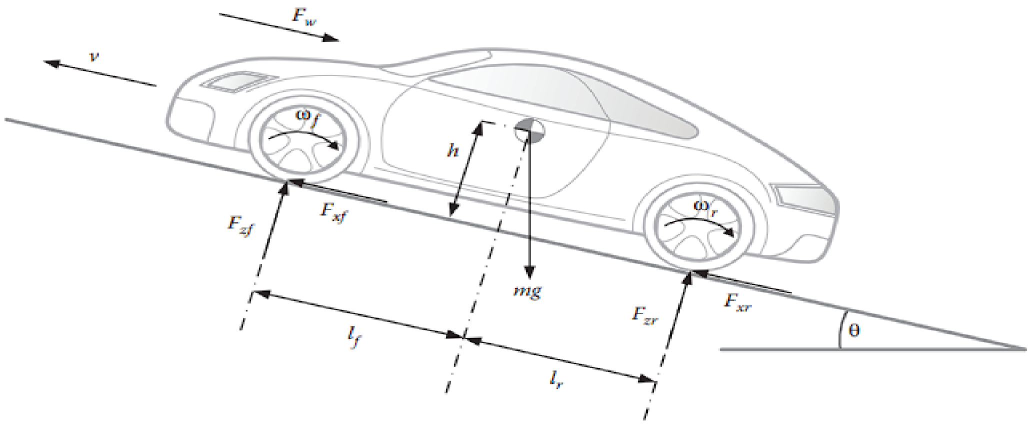

FIGURE 2.1 Forces acting on a vehicle.

2.2 LONGITUDINAL RESISTANCE

2.2.1 Aerodynamic Drag

As air travels over the body of the vehicle, it generates normal pressure and shear stress on the vehicle's body. The external aerodynamic resistance is comprised of two components, shape drag and skin friction. The shape drag arises from high-pressure areas in front of the vehicle and low-pressure areas behind the vehicle that are created as the vehicle propels itself through the air. These high-and low-pressure zones act against the motion of the vehicle, while the skin friction is due to the shear stress in the boundary layer on the surface of the body of the vehicle. In comparison, shape drag is much larger in magnitude than skin friction and constitutes more than 90% of the total external aerodynamic drag of a vehicle. Aerodynamic drag is a function of effective vehicle frontal area, A, and the aerodynamic drag coefficient, C_d, which are highly dependent on the design of the vehicle body:

$$F_w = \frac{1}{2}\rho A C_d (V + V_w)^2 \tag{2.2}$$

where ρ is the air density, V is the vehicle longitudinal speed, and V_w is the wind speed.

2.2.2 Grading Resistance

As a vehicle travels up or down an incline, gravity acting on the vehicle produces a force which is always directed downward, as shown in Figure 2.1. This force opposes the forward motion during grade climbing and aids in the forward motion during grade descending. In typical vehicle performance models, only uphill operation is considered as it resists the total tractive force. The equation for this force is a function of the road angle θ, vehicle mass *m*, and the gravitational acceleration *g*:

$$F_g = mg\sin(\theta) \tag{2.3}$$

For a relatively small angle of θ, tan θ = sin θ. Using this approximation, the grade resistance can be approximated by *mg* tan θ, or *mgG*, where *G* is the slope of the grade.

2.2.3 Rolling Resistance

Rolling resistance force is a result of the hysteresis of the tire at the contact patch as it rolls along the roadway. In a stationary tire, the normal force due to the road balances the force due to the weight of the vehicle through the contact patch which is in line with the center of the tire. When the tire rolls, as a result of tire distortion or hysteresis, the normal pressure in the leading half of the contact patch is higher than that in the trailing half. The normal force due to the road is shifted from the center of the tire in the direction of motion. This shift produces a moment that exerts a retarding torque on the wheel. The rolling resistance force is the force due to the moment, which opposes the motion of the wheel, and always assists in braking or retarding the motion of the vehicle. The equation for this force is a function of the normal load F_z and the rolling resistance coefficient f_r, which is derived by dividing the distance the normal force due to the road is shifted by the effective radius of the tire r_d.

$$F_r = F_z f_r \cos(\theta) \tag{2.4}$$

2.3 TOTAL TRACTIVE FORCE

Equation 2.1 shows the factors affecting vehicle performance with a particular interest in the overall tractive force of the vehicle.

$$ma = F_t - F_w - F_g - F_r \Rightarrow ma = (F_{tf} + F_{tr}) - (F_w + F_g + F_{rf} + F_{rr}) \tag{2.5}$$

By rearranging Equation 2.1 we arrive at an equation that expresses longitudinal vehicle motion as a combination of total tractive effort minus the resistance. In order to determine the total tractive effort, the normal forces, F_{zf} and F_{zr}, need to be determined. The front and rear tire contact points should satisfy the equilibrium equations for moments:

$$\sum M_r = 0, \quad \sum M_f = 0 \tag{2.6}$$

Therefore,

$$F_{zf}(l_f + l_r) + F_w h_w + (mg\sin(\theta)h) + (mah) - (mg\cos(\theta)l_r) = 0 \tag{2.7}$$

and

$$F_{zr}(l_f + l_r) - F_w h_w - (mg\sin(\theta)h) - (mah) - (mg\cos(\theta)l_f) = 0 \tag{2.8}$$

where F_{zf} and F_{zr} are the normal forces on the front and rear tires, l_f and l_r are the distances between the front and rear axles and vehicle center of gravity, respectively. h_w is the height for effective aerodynamic drag force and h is the height of vehicle center of gravity. For simplicity, usually h_w is assumed to be equal to h. Equations 2.7 and 2.8 can be rearranged to solve for the normal forces on the front and rear tires:

$$F_{zf} = \frac{-F_w h - mg\sin(\theta)h - mah + mg\cos(\theta)l_r}{l_f + l_r} \tag{2.9}$$

$$F_{zr} = \frac{F_w h + mg\sin(\theta)h + mah + mg\cos(\theta)l_f}{l_f + l_r} \tag{2.10}$$

The total tractive force can be expressed as the tractive forces acting on each tire:

$$F_t = F_{xf} + F_{xr} \tag{2.11}$$

where F_{xf} and F_{xr} are the longitudinal forces on the front and rear tires, respectively. The friction generated between the tire–road contact patch creates the longitudinal force. Therefore, the longitudinal force generated on each tire can be represented as a function of the tire friction coefficient and the normal force:

$$F_{xf} = \mu_f F_{zf}, \quad F_{xr} = \mu_r F_{zr} \tag{2.12}$$

where F_{xf} and F_{zr} are the normal forces on the front and rear tires given by Equations 2.9 and 2.10 and μ_f and μ_r are the friction coefficients on the front and rear tires, respectively.

2.Drive cycles:

12.3 DRIVING CYCLES

Driving cycles and terrain conditions are critical factors, which influence energy saving and emission reduction to a large extent.

Driving cycle is defined as the velocity variation of the vehicle with respect to the time under different driving conditions. For example, you could have noticed that highway driving differs significantly compared to city driving. In city driving, there are a lot of traffic signals and speed limits, and depending upon the traffic conditions, the driver has to go through frequent stop-and-go-type driving. On the other hand, this is not the case in highway driving conditions. In highway driving, the vehicle does not accelerate too often and most of the time it cruises with a constant velocity (except for overtaking and lane changing). In general, common driving cycles can be categorized into four different types, as shown in Figure 12.2. It includes three types of highway driving cycles such as a smooth highway driving, highway driving cycles with frequent lane changing and overtaking, and highway driving cycles with unexpected traffic idling, and frequent stop-and-go-type city driving cycles. It can be noted from Figure 12.2a that in smooth highway driving, the vehicle accelerates at the beginning to reach an expected speed limit and it continuously cruises with a constant velocity for a significant period and then decelerates to exit the highway. Figure 12.2b shows another type of highway driving cycle, where the driver demands the vehicle to go through frequent overtaking and lane-changing activities. As depicted in Figure 12.2c, in the third type of highway driving cycle, the vehicle goes through unexpected traffic idling. Although it has been divided into three different categories, a combination of all three could also be possible in real highway driving conditions. Figure 12.2d shows frequent stop-and-go-type city driving conditions.

There are many studies that suggest that driving pattern variations are not only decided by external factors such as traffic and other conditions, but also by the driver's age, weather condition, type of vehicle they drive, and so on. Therefore, it is very hard to generalize a single driving cycle, which represents all possible real-world driving scenarios. In this section, we have discussed a few common driving cycles and how they are different from each other. The next section describes the connection between the driving cycle fuel economy enhancement and emission reduction of the vehicle.

12.3.1 Effect of Driving Cycles on Fuel Economy Enhancement and Emission Reduction

To understand the effect of driving cycle on fuel economy enhancement and emission reduction, the understanding of vehicle dynamics is very important. Therefore, this section provides a small introduction to simplified vehicle dynamics, which provides the necessary ground work.

Figure 12.3 shows a simplified vehicle dynamics, where the vehicle is accelerating with an acceleration rate of a from a velocity V in a road, which makes an angle B to the horizontal. In this driving condition, the propulsive force required to achieve this objective can be given by

$$F_p - F_{r\_f} - F_{r\_r} - F_{aero} - Mg\sin(B) = Ma \tag{12.1}$$

Here

F_p: force exerted on the drive wheels by the propulsive system of the vehicle (N)
F_{r_f}, F_{r_r}: the ground resistance on the front and rear wheels of the vehicle (N)
F_{aero}: aerodynamic drag force (N)
a: acceleration of the vehicle (m/s^2)
M: mass of the vehicle (kg)
V: velocity of the vehicle (m/s)

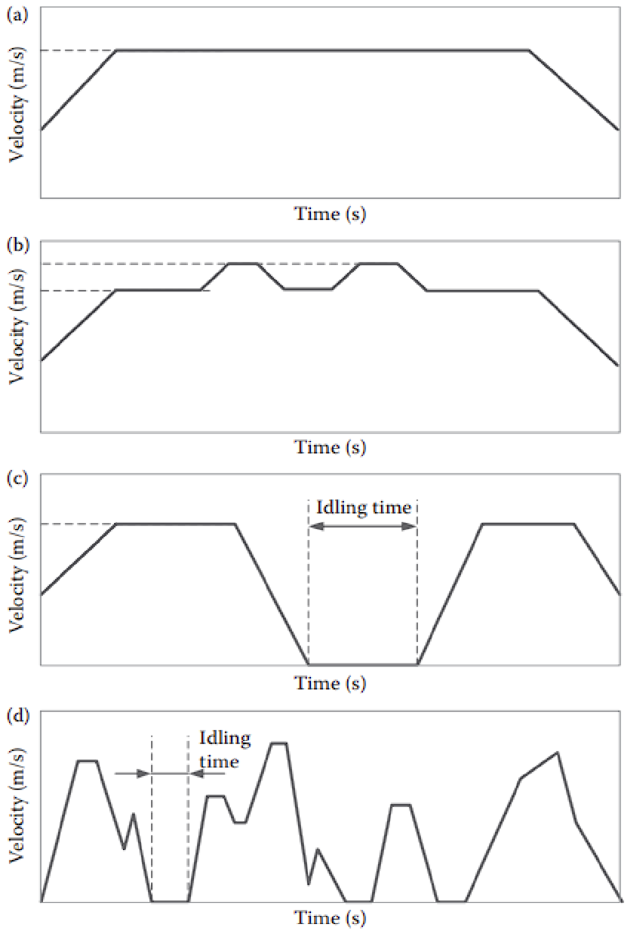

FIGURE 12.2 Different types of real-world driving cycles: (a) Smooth highway driving; (b) highway driving with frequent overtaking and lane-changing activities; (c) highway driving with the unexpected traffic idling; (d) frequent stop-and-go-type city driving.

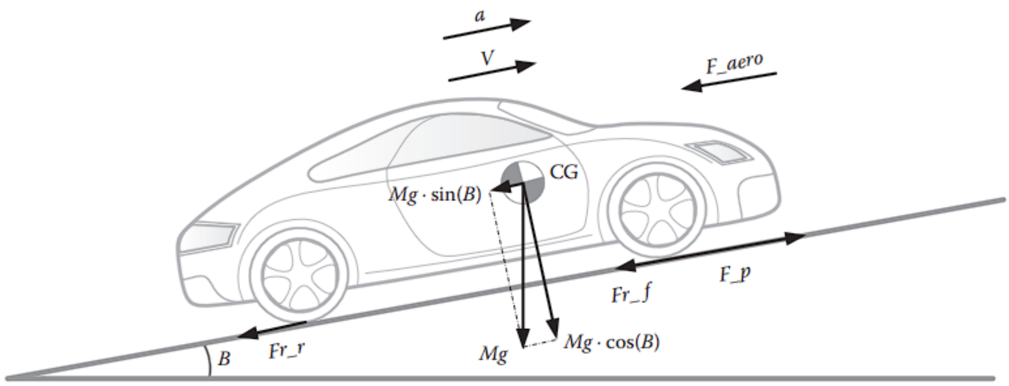

FIGURE 12.3 Simplified force diagram of the vehicle.

B: inclination angle of the road
CG: center of gravity of the vehicle

From Equation 12.1, the propulsive power requirement of the vehicle can be derived as

$$P_p = (F_{r\_f} + F_{r\_r} + F_{aero} + Mg\sin(B) + Ma)V \tag{12.2}$$

Here, P_P is propulsive power of the vehicle (W).

The force due to ground resistance can be given by Equation 12.3. This is a function of the mass of the vehicle, road inclination angle, and the adhesive coefficient υ of the road. In general, the adhesive coefficient of the road is very less (between 0.2 and 0.4); therefore, the force due to ground resistance will not go beyond a kilowatt for a typical passenger car under any driving circumstance.

$$F_{r\_f} + F_{r\_r} = \upsilon Mg\cos(B) \tag{12.3}$$

To make it simpler, let us neglect the ground resistance and assume that the vehicle is traveling on a flat road. Therefore, the power requirement of the vehicle can be further simplified as Equation 12.4.

$$P_p = (F_{aero} + Ma)V \tag{12.4}$$

The power required to overcome the aerodynamic resistance can be written as

$$P_{aero} = \frac{1}{2}\rho A C_D V^3 \tag{12.5}$$

Here, the cross-sectional area of the vehicle is given by A, air density is given by ρ, and the aerodynamic drag coefficient of the vehicle is given by C_D. As one can note from Equation 12.5, aerodynamic power holds a linear relationship with the third order of the vehicle velocity. Therefore, the power required to overcome the aerodynamic resistance is significantly high at high-speed conditions and is negligible at low speeds.

The acceleration power of the vehicle can be given by Equation 12.6.

$$P_{acc} = MaV \tag{12.6}$$

As one can note here, the power required to accelerate the vehicle is a function of the vehicle mass M, acceleration rate of the vehicle a, and the velocity of the vehicle V. Since the mass of the

vehicle will remain constant over a given driving condition, the vehicle's velocity V and the expected acceleration rate a at that velocity will determine the acceleration power requirement of the vehicle.

Integrating the propulsive power requirement with respect to time will provide the energy requirement of the vehicle. Therefore, the energy required to achieve a particular driving requirement can be given by Equation 12.7.

$$E_{propulsion} = \int_{t_0}^{t_1} \left(MaV + \frac{1}{2}\rho A C_D V^3 \right) dt \tag{12.7}$$

It should be noted here that vehicle acceleration a and velocity V are time-dependent variables.

Applying these equations to a particular driving cycle, one can calculate the power and energy requirements of the propulsive system to fulfill different phases of the driving cycle. To find out the variation in power and energy requirement, let us investigate a case study.

Drive terrain:

12.4 DRIVING CYCLES AND ROAD CONDITIONS ON FUEL ECONOMY

So far, we have assumed flat road driving condition to perform our analysis. However, it is not a valid assumption, since real-world road conditions are not flat as we prefer. In practice, vehicles should be able to drive uphill, downhill, and in flat terrain environments. It implies that vehicles should be able to achieve expected driving cycles in different terrain environments. Therefore, realistic driving cycles should incorporate the geographical information of the road and the velocity variation of the vehicle over the entire duration of the driving.

Figure 12.6 shows all of the driving cycles discussed in Section 12.2, with all possible geographical information. Now, the propulsive power requirement to accomplish the same driving cycles in

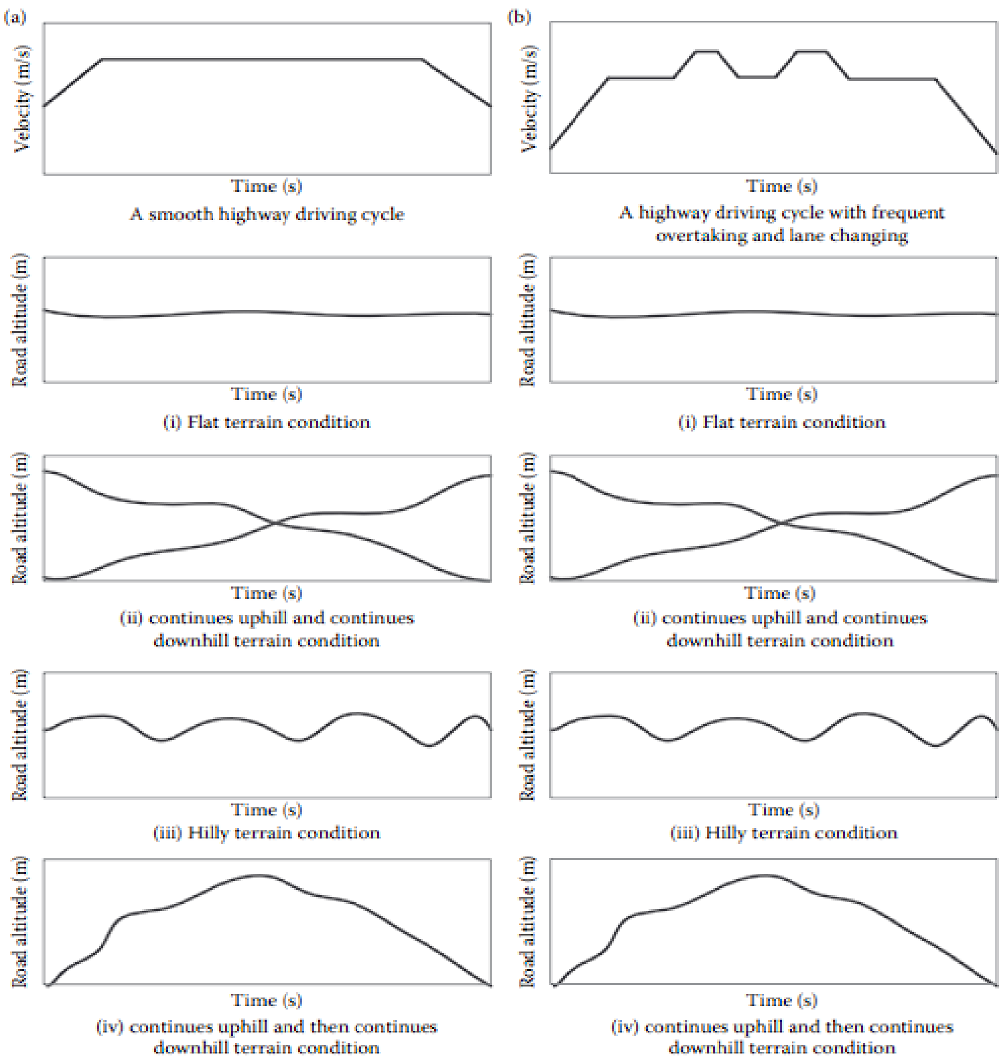

FIGURE 12.6 Driving cycle with terrain information: (a) Smooth highway driving in different road conditions and (b) highway driving with frequent overtaking and lane-changing activities.

different road condition will vary. However, it should be verified how significant it is on the fuel efficiency of the vehicle. Therefore, let us perform another case study to investigate the effect of driving terrain condition on fuel economy.

3.Concept of electric vehicle:

INTRODUCTION TO ELECTRIC VEHICLES:

Electric vehicles paved their way into public use as early as the middle of the 19th century, even before the introduction of gasoline-powered vehicles.2 In the year 1900, 4200 automobiles were sold, out of which 40% were steam powered, 38% were electric powered, and 22% were gasoline powered. However, the invention of the starter motor, improvements in mass production technology of gas-powered vehicles, and inconvenience in battery charging led to the disappearance of the EV in the early 1900s. However, environmental issues and the unpleasant dependence on oil led to the resurgence of interest in EVs in the 1960s. Growth in the enabling technologies added to environmental and economic concerns over the next several decades, increasing the demand for investing in research and development for EVs. Interest and research in EVs soared in the 1990s, with the major automobile manufacturers embarking on plans for introducing their own electric or hybrid electric vehicles. The trend increases today, with EVs serving as zero-emission vehicles, and hybrid electric vehicles already filling in for ultralow-emission vehicles

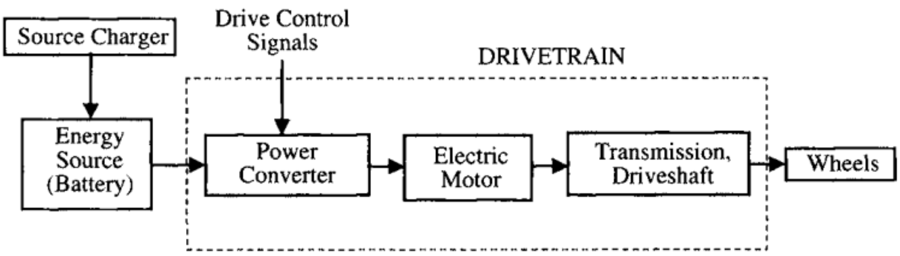

FIGURE 1.1 Top-level perspective of an EV system.

An EV has the following two features:

1. The energy source is portable and chemical or electromechanical in nature.

2. Traction effort is supplied only by an electric motor.

Figure 1.1 shows an EV system driven by a portable energy source. The electromechanical energy conversion linkage system between the vehicle energy source and the wheels is the drivetrain of the vehicle. The drivetrain has electrical as well as mechanical components.

COMPONENTS OF AN EV:

The primary components of an EV system are the motor, controller, power source, and transmission. The detailed structure of an EV system and the interaction among its various components are shown in Figure 1.2. Figure 1.2 also shows the choices available for each of the subsystem level components. Electrochemical batteries have been the traditional source of energy in EVs. Lead-acid batteries have been the primary choice, because of their well developed technology and lower cost, although promising new battery technologies are being tested in many prototype vehicles. The batteries need

a charger to restore the stored energy level once its available energy is near depletion due to usage. Alternative energy sources are also being developed for

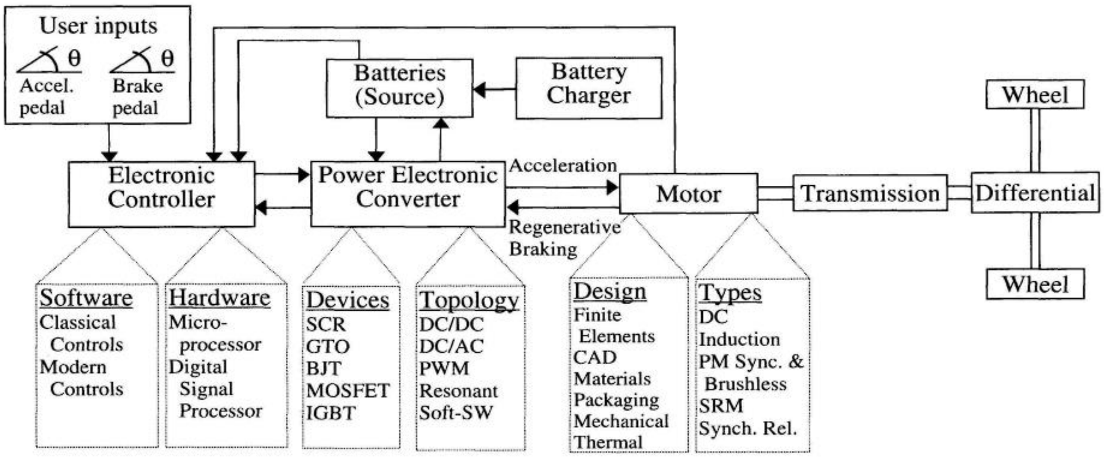

FIGURE 1.2 Major electrical components and choices for an EV system.

zero-emission vehicles. The limited range problem of battery-driven EVs prompted the search for alternative energy sources, such as fuel cells and flywheels. Prototypes have been developed with fuel cells, while production vehicles will emerge in the near future. The majority of electric vehicles developed so far are based on DC machines, induction machines, or permanent magnet machines. The disadvantages of DC machines pushed EV developers to look into various types of AC machines. The maintenance-free, low-cost induction machines became an attractive alternative to many developers. However, high-speed operation of induction machines is only possible with a penalty in size and weight. Excellent performance together with high-power density features of permanent magnet machines make them an attractive solution for EV applications, although the cost of permanent magnets can become prohibitive. High-power density and a potentially low production cost of switched reluctance machines make them ideally suited for EV applications. However, the acoustic noise problem has so far been a deterrent for the use of switched reluctance machines in EVs. The electric motor design includes not only electromagnetic aspects of the machine but also thermal and mechanical considerations. The motor design tasks of today are supported by finite element studies and various computer-aided design tools, making the design process highly efficient. The electric motor is driven by a power-electronics-based power-processing unit that converts the fixed DC voltage available from the source into a variable voltage, variable frequency source controlled to maintain the desired operating point of the vehicle. The power electronics circuit comprised of power semiconductor devices saw tremendous development over the past 3 decades. The enabling technology of power electronics is a key driving force in developing efficient and high-performance power-train units for EVs. High-power devices in compact packaging are available today, enabling the development of lightweight and efficient power-processing units known as power electronic motor drives. Advances in power solid state devices and very large-scale integration (VLSI) technology are responsible for the development of efficient and compact power electronics circuits. The developments in high-speed digital signal processors or microprocessors enable complex control algorithm implementation with a high degree of accuracy. The controller includes algorithms for the motor drive in the inner loop as well as system-level control in the outer loop.

Concept of Hybrid Electric vehicle:

5.1 Concept of Hybrid Electric Drive Trains

Basically, any vehicle power train is required to (1) develop sufficient power to meet the demands of vehicle performance, (2) carry sufficient energy onboard to support vehicle driving in the given range, (3) demonstrate high efficiency, and (4) emit few environmental pollutants. Broadly, a vehicle may have more than one energy source and energy converter (power source), such as a gasoline (or diesel) heat engine system, hydrogen–fuel cell–electric motor system, chemical battery–electric motor system, etc. A vehicle that has two or more energy sources and energy converters is called a hybrid vehicle. A hybrid vehicle with an electrical power train (energy source energy converters) is called an HEV.

A hybrid vehicle drive train usually consists of no more than two power trains. More than two power train configurations will complicate the system. For the purpose of recapturing part of the braking energy[8] that is dissipated in the form of heat in conventional ICE vehicles, a hybrid drive train usually has a bidirectional energy source and converter. The other one is either bidirectional or unidirectional. Figure 5.1 shows the concept of a hybrid drive train and the possible different power flow routes.

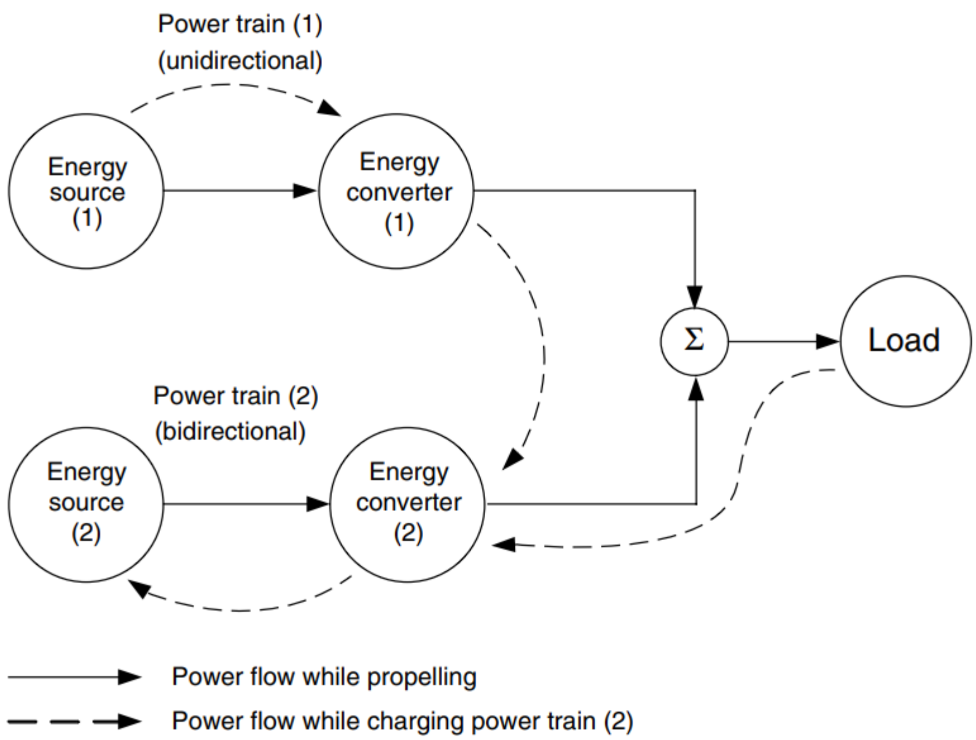

FIGURE 5.1
Conceptual illustration of a hybrid electric drive train

Hybrid drive trains supply the required power by an adapted power train. There are many available patterns of combining the power flows to meet load requirements as described below:

1. Power train 1 alone delivers power to the load
2. Power train 2 alone delivers power to the load
3. Both power train 1 and 2 deliver power to load at the same time
4. Power train 2 obtains power from load (regenerative braking)
5. Power train 2 obtains power from power train 1
6. Power train 2 obtains power from power train 1 and load at the same time
7. Power train 1 delivers power to load and to power train 2 at the same time
8. Power train 1 delivers power to power train 2, and power train 2 delivers power to load
9. Power train 1 delivers power to load, and load delivers power to power train 2.

In the case of hybridization with a liquid fuel-IC engine (power train 1) and a battery-electric machine (power train 2), pattern (1) is the engine-alone propelling mode. This may be used when the batteries are almost completely depleted and the engine has no remaining power to charge the batteries, or when the batteries have been fully charged and the engine is able to supply sufficient power to meet the power demands of the vehicle. Pattern (2) is the pure electric propelling mode, in which the engine is shut off. This pattern may be used in situations where the engine cannot operate effectively, such as very low speed, or in areas where emissions are strictly prohibited. Pattern (3) is the hybrid traction mode and may be used when a large amount of power is needed, such as during sharp acceleration or steep hill climbing. Pattern (4) is the regenerative braking mode, by which the kinetic or potential energy of the vehicle is recovered through the electric motor functioning as a generator. The recovered energy is stored in the batteries and reused later on. Pattern (5) is the mode in which the engine charges the batteries while the vehicle is at a standstill, coasting, or descending a slight grade, in which no power goes into or comes from the load. Pattern (6) is the mode in which both regenerative braking and the IC engine charge the batteries simultaneously. Pattern (7) is the mode in which the engine propels the vehicle and charges the batteries simultaneously. Pattern (8) is the mode in which the engine charges the batteries, and the batteries supply power to the load. Pattern (9) is the mode in which the power flows into the batteries from the heat engine through the vehicle mass. The typical configuration of this mode is two power trains separately mounted on the front and the rear axle of the vehicle.

The varied operation modes in a hybrid vehicle create more flexibility over a single power train vehicle. With proper configuration and control, applying the specific mode for each special operating condition can optimize overall performance, efficiency, and emissions. However, in a practical

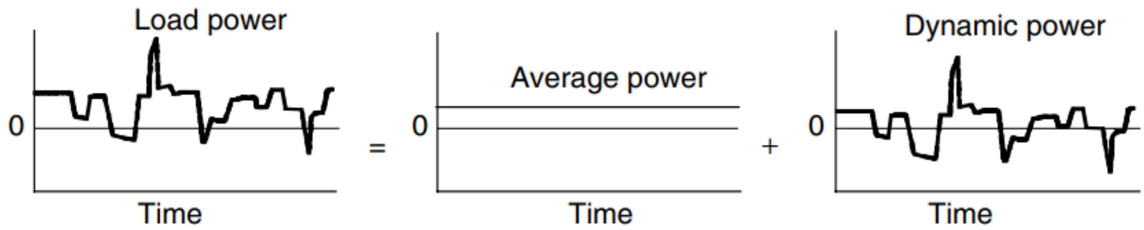

FIGURE 5.2
A load power is decomposed into steady and dynamic components

design, deciding which mode should be implemented depends on many factors, such as the physical configuration of the drive train, the power train efficiency characteristics, load characteristics, etc.

Operating each power train in its optimal efficiency region is essential for the overall efficiency of the vehicle. An IC engine generally has the best efficiency operating region with a wide throttle opening. Operating away from this region will cause the efficiency to suffer a lot (refer to Figures 2.30, 2.32, 2.34, and 2.35). On the other hand, efficiency suffering in an electric motor is not as detrimental when compared to an IC engine that operates away from its optimal region (refer to Figure 3.14).

The load power of a vehicle varies randomly in real operation due to frequent acceleration, deceleration, and climbing up and down grades, as shown in Figure 5.2. Actually, the load power is composed of two components: one is steady (average) power, which has a constant value, and the other is dynamic power, which has a zero average. In hybrid vehicle strategy, one power train that favors steady-state operation, such as an IC engine fuel cell, can be used to supply the average power. On the other hand, other power trains such as an electric motor can be used to supply the dynamic power. The total energy output from the dynamic power train will be zero in a whole driving cycle. This implies that the energy source of the dynamic power train does not lose energy capacity at the end of the driving cycle. It functions only as a power damper.

In a hybrid vehicle, steady power may be provided by an IC engine, a Stirling engine, a fuel cell, etc. The IC engine or the fuel cell can be much smaller than that in a single power train design because the dynamic power is taken by the dynamic power source, and can then operate steadily in its most efficient region. The dynamic power may be provided by an electric motor powered by electrochemical batteries, ultracapacitors, flywheels (mechanical batteries), and their combinations.[1–3]

4.History of Hybrid Electric Vehicles:

The concept of a hybrid electric vehicle is almost as old as the automobile itself. The primary purpose, however, was not so much to lower the fuel consumption but rather to assist the ICE to provide an acceptable level of performance. Indeed, in the early days, ICE engineering was less advanced than electric motor engineering. The first hybrid vehicles reported were shown at the Paris Salon of 1899. The Pieper was undoubtedly the first electric starter, the Pieper vehicle was a parallel hybrid with a small air-cooled gasoline engine assisted by an electric motor and lead–acid batteries. It is reported that the batteries were charged by the engine when the vehicle coasted or was at a standstill. When the driving power required was greater than the engine rating, the electric motor provided additional power. The other hybrid vehicle introduced at the Paris Salon of 1899 was the first series hybrid electric vehicle and was derived from a pure electric vehicle commercially built by the French firm Vendovelli and Priestly [13]. This vehicle was a tricycle, with the two rear wheels powered by independent motors. An additional 3/4 hp gasoline engine coupled to a 1.1 kW generator vehicle to extend its range by recharging the batteries. In the French case, the hybrid design was used to extend the range of an electric vehicle, and not to supply additional power to a weak ICE. Frenchman Camille Jenatzy presented a parallel hybrid vehicle at the Paris Salon of 1903. This vehicle combined a 6 hp gasoline engine with a 14 hp electric machine that could either charge the batteries from the engine or assist them later. Another Frenchman, H. Krieger, built the second reported series hybrid vehicle in 1902. His design used two independent DC motors driving the front wheels. They drew their energy from 44 lead–acid cells that were recharged by a 4.5 hp alcohol spark-ignited engine coupled to a shunt DC generator. During a period ranging from 1899 until 1914. dynamic braking were used in all designs. After the first world war 1, the gasoline engine with tremendous improvements in terms of power density , small size and was no longer a need to assist them with electric motors. The great problem with early designs was the difficulty of controlling the electric machine since power electronics did not become available until mid 1960's. In 1975, Dr.Victor Wouk along with his colleagues, he built a parallel hybrid version of a Buick Skylark.13 The engine was a Mazda rotary engine, It was assisted by a 15 hp separately excited DC machine, Eight 12 V automotive batteries were used for energy storage. A top speed of 80 mph (129 km/h) was achieved with acceleration from 0 to 60 mph in 16 sec. In 1982 parallel hybrid vehicle were built by electric auto corporation and by Briggs & Stratton corporation in 1980. Despite the two oil crises of 1973 and 1977, and despite growing environmental concerns, no hybrid electric vehicle made it to the market. In 1980's automobile manufacturers built proto types that achieved tremendous improvements in fuel economy over ICE-powered counterparts. In 1997, Toyota released the Prius sedan in Japan. Honda also released its Insight and Civic Hybrid. These vehicles are now available throughout the world. They achieve excellent figures of fuel consumption.

5.ADVANTAGES OF ELECTRIC VEHICLE:

1.3
EV ADVANTAGES

The relative advantages and disadvantages of an EV over an ICEV can be better appreciated from a comparison of the two on the bases of efficiency, pollution, cost, and dependence on oil. The comparison must be executed with care, ensuring fairness to both systems.

1.3.1
EFFICIENCY COMPARISON

To evaluate the efficiencies of EV and ICEV on level ground, the complete process in both systems starting from crude oil to power available at the wheels must be considered. The EV process starts not at the vehicles, but at the source of raw power whose conversion efficiency must be considered to calculate the overall efficiency of electric vehicles. The power input P_{IN} to the EV comes from two sources—the stored power source and the applied power source. Stored power is available during the process from an energy storage device. The power delivered by a battery through electrochemical reaction on demand or the power extracted from a piece of coal by burning it are examples of stored power. Applied power is obtained indirectly from raw materials. Electricity generated from crude oil and delivered to an electric car for battery charging is an example of applied power. Applied power is labeled as $P_{IN\ AW}$ while stored power is designated as $P_{IN\ PROCESS}$ in Figure 1.3. Therefore, we have the following:

$$P_{IN} = P_{IN\ PROCESS} + P_{IN\ RAW}$$

The complete EV process can be broken down into its constituent stages involving a chain of events responsible for power generation, transmission, and usage, as shown in Figure 1.4. Raw power from the applied source is fed to the system only at the first stage, although stored power can be added in each stage. Each stage has its efficiency based on total input to that stage and output delivered to the following stage. For example, the efficiency of the first stage based on the input and output shown in Figure 1.4 is

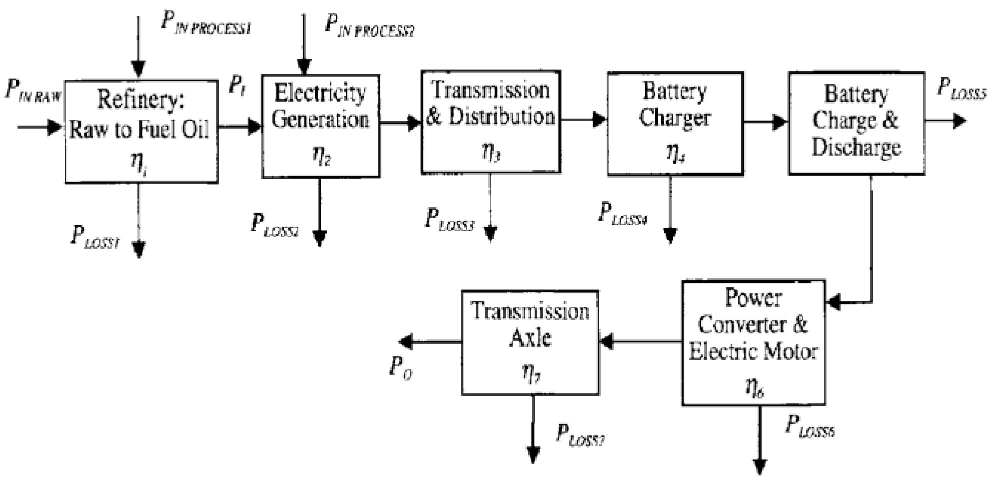

FIGURE 1.4 The complete EV process broken into stages.

$$\eta_1 = \frac{P_1}{P_{IN\,RAW} + P_{IN\,PROCESS1}}$$

The efficiency of each stage must be calculated from input-output power considerations, although the efficiency may vary widely, depending on the technology being used. Finally, overall efficiency can be calculated by multiplying the efficiencies of the individual stages. The overall efficiency of the EV system shown in Figure 1.4 is

$$\eta_{EV} = \frac{P_0}{P_{IN}} = \frac{P_0}{P_0 + \sum_{i=1}^{7} P_{LOSSi}} = \eta_1\eta_2\eta_3\eta_4\eta_5\eta_6\eta_7$$

The overall ICEV process is shown in Figure 1.5, while the process details are illustrated in Figure 1.6. Starting from the conversion of crude oil to fuel oil in the refinery, the ICEV process includes the transmission of fuel oil from refinery to gas stations, power conversion in the internal combustion engine of the vehicle, and power transfer from the engine to the wheels through the transmission before it is available at the wheels. The efficiency of the ICEV process is the product of the efficiencies of the individual stages indicated in Figure 1.6 and is given by

$$\eta_{ICEV} = \eta_1\eta_2\eta_3\eta_4$$

A sample comparison of EV and ICEV process efficiencies based on the diagrams of Figure 1.4 and 1.6 is given in Table 1.2. Representative numbers have been used for the energy conversion stages in each process to convey a general idea of the efficiencies of the two systems. From Table 1.2, it can be claimed that the overall efficiency of an EV is comparable to the overall efficiency of an ICEV.

TABLE 1.2 EV and ICEV Efficiencies from Crude Oil to Traction Effort

ICEV	Efficiency (%) Max.	Efficiency (%) Min.	EV	Efficiency (%) Max.	Efficiency (%) Min.
Crude oil			Crude oil		
Refinery (petroleum)	90	85	Refinery (fuel oil)	97	95
Distribution to fuel tank	99	95	Electricity generation	40	33
Engine	22	20	Transmission to wall outlet	92	90
Transmission/axle	98	95	Battery charger	90	85
Wheels			Battery (lead/acid)	75	75
			Motor/controller	85	80
			Transmission/axle	98	95
			Wheels		
Overall efficiency (crude oil to wheels)	19	15	Overall efficiency (crude oil to wheels)	20	14

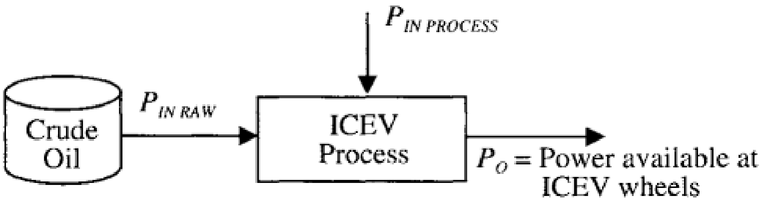

FIGURE 1.5 ICEV process from crude oil to power at the wheels.

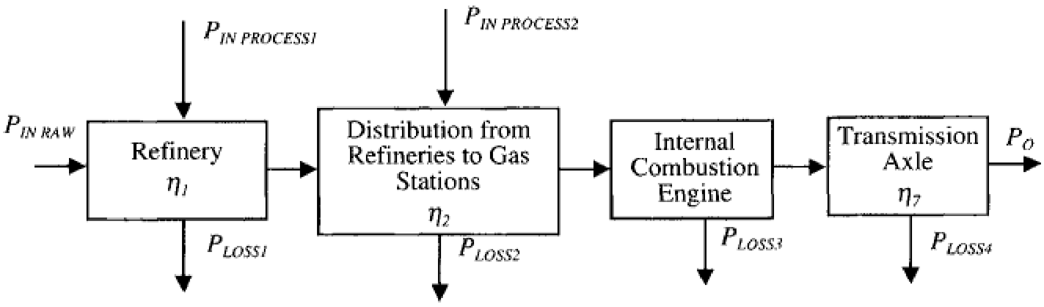

FIGURE 1.6 The complete ICEV process broken into stages.

1.3.2
POLLUTION COMPARISON

Transportation accounts for one third of all energy usage, making it the leading cause of environmental pollution through carbon emissions.[5] The DOE projected that if 10% of automobiles nationwide were zero-emission vehicles, regulated air pollutants would be cut by 1,000,000 tons per year, and 60,000,000 tons of green-house carbon dioxide gas would be eliminated. With 100% electrification, i.e., every ICEV replaced by an EV, the following was claimed:

- Carbon dioxide in air, which is linked to global warming, would be cut in half.
- Nitrogen oxides (a greenhouse gas causing global warming) would be cut slightly, depending on government-regulated utility emission standards.
- Sulfur dioxide, which is linked to acid rain, would increase slightly.
- Waste oil dumping would decrease, because EVs do not require crankcase oil.
- EVs reduce noise pollution, because they are quieter than ICEVs.
- Thermal pollution by large power plants would increase with increased EV usage.

EVs will considerably reduce the major causes of smog, substantially eliminate ozone depletion, and reduce greenhouse gases. With stricter SO_2 power plant emission standards, EVs would have little impact on SO_2 levels. Pollution reduction is the driving force behind EV usage

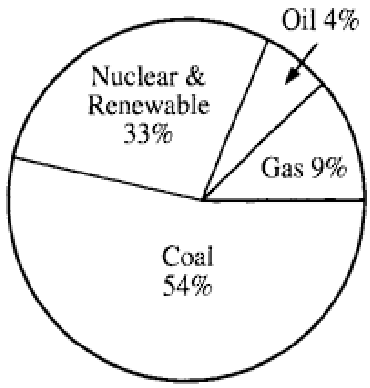

FIGURE 1.7 Electricity generation Piechart

1.3.3
CAPITAL AND OPERATING COST COMPARISON

The initial EV capital costs are higher than ICEV capital costs primarily due to the lack of mass production opportunities. However, EV capital costs are expected to decrease as volume increases. Capital costs of EVs easily exceed capital costs of ICEVs due to the cost of the battery. The power electronics stages are also expensive, although not at the same level as batteries. Total life cycle cost of an EV is projected to be less than that of a comparable ICEV. EVs are more reliable and will require less maintenance, giving a favorable bias over ICEV as far as operating cost is concerned.

1.3.4
U.S. DEPENDENCE ON FOREIGN OIL

The importance of searching for alternative energy sources cannot be overemphasized, and sooner or later, there will be another energy crisis if we, the people of the earth, do not reduce our dependence on oil. Today's industries, particularly the transportation industry, are heavily dependent on oil, the reserve of which will eventually deplete in the not so distant future. Today, about 42% of petroleum used for transportation in the United States is imported. An average ICEV in its lifetime uses 94 barrels of oil, based on 28 mi/gallon fuel consumption. On the other hand, an average EV uses two barrels of oil in its lifetime, based on 4 mi/kWh. The oil is used in the EV process during electricity generation, although only 4% of electricity generated is from oil. The energy sources for electricity generation are shown in the pie chart of Figure 1.7.

1.4
EV MARKET

We normally discuss the use of EVs for passenger and public transportation but tend to forget about their use as off-road vehicles in specialty applications, where range is not an issue. EVs have penetrated the market of off-road vehicles successfully over the years for clean air as well as for cost advantages. Examples of such applications are airport vehicles for passenger and ground support; recreational vehicles as in golf carts and for theme parks, plant operation vehicles like forklifts and loader trucks; vehicles for disabled persons; utility vehicles for ground transportation in closed but large compounds; etc. There are also EVs that run on tracks for material haulage in mines. There is potential for EV use for construction vehicles. The locomotives that run on tracks with electricity supplied from transmission lines are theoretically no different from other EVs, the major difference being in the way energy is fed for the propulsion motors.

Motivated by the growing concern about global pollution and the success of electric motor driven transportation in various areas, the interest is ever increasing for road EVs that can deliver the performance of ICEV counterparts. The major impediments for mass acceptance of EVs by the general public are the limited EV range and the lack of EV infrastructure. The solution of the range problem may come from extensive research and development efforts in batteries, fuel cells, and other alternative energy storage devices. An alternative approach is to create awareness among people on the problems of global warming and the advantages of EVs, while considering the fact that most people drive less than 50 miles a day, a requirement that can be easily met by today's technology.

The appropriate infrastructure must also be in place for EVs to become more popular. The issues related to infrastructure are as follows:

- Battery charging facilities: residential and public charging facilities and stations
- Standardization of EV plugs, cords, and outlets, and safety issues
- Sales and distribution
- Service and technical support
- Parts supply

The current initial cost of an EV is also a big disadvantage for the EV market. The replacement of the batteries, even for HEVs, is quite expensive, added to which is the limited life problem of these batteries. The cost of EVs will come down as volume goes up, but in the meantime, subsidies and incentives from the government can create momentum.

The increasing use of EVs will improve the job prospects of electrical engineers. The new jobs related to EVs will be in the following areas:

• Power electronics and motor drives: Design and development of the electrical systems of an EV

• Power generation: Increased utility demand due to EV usage

• EV infrastructure: Design and development of battery charging stations and of hydrogen generation, storage and distribution systems.

Advantages of Hybrid Electric Vehicles:

Today's hybrid electric vehicles (HEVs) are powered by an internal combustion engine in combination with one or more electric motors that use energy stored in batteries. HEVs combine the benefits of high fuel economy and low tailpipe emissions with the power and range of conventional vehicles.

A wide variety of HEV models are currently available. Although HEVs are often more expensive than similar conventional vehicles, some cost may be recovered through fuel savings or state incentives.

Help from an Electric Motor

In an HEV, the extra power provided by the electric motor may allow for a smaller combustion engine. The battery can also power auxiliary loads and reduce engine idling when the vehicle is stopped. Together, these features result in better fuel economy without sacrificing performance.

Regenerative Braking

An HEV cannot plug in to off-board sources of electricity to charge the battery. Instead, the vehicle uses regenerative braking and the internal combustion engine to charge. The vehicle captures energy normally lost during braking by using the electric motor as a generator and storing the captured energy in the battery.

Fuel-Efficient System Design

HEVs can be either mild or full hybrids, and full hybrids can be designed in series or parallel configurations.

- **Mild hybrids**—also called micro hybrids—use a battery and electric motor to help power the vehicle and can allow the engine to shut off when the vehicle stops (such as at traffic lights or in stop-and-go traffic), further improving fuel economy. Mild hybrid systems cannot power the vehicle using electricity alone. These vehicles generally cost less than full hybrids but provide less fuel economy benefit than full hybrids.

- **Full hybrids** have larger batteries and more powerful electric motors, which can power the vehicle for short distances and at low speeds. These vehicles cost more than mild hybrids but provide better fuel economy benefits.

There are different ways to combine the power from the electric motor and the engine. **Parallel hybrids**—the most common HEV design—connect the engine and the electric motor to the wheels through mechanical coupling. Both the electric motor and the internal combustion engine drive the wheels directly. **Series hybrids**, which use only the electric motor to drive the wheels, are more commonly found in plug-in hybrid electric vehicles.